Excitation Functions for Two Nitrogen-Sodium Nuclear Reactions

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Excitation functions were measured for two nitrogen-induced nuclear reactions on sodium, $Na^{23}(N^{14},\alpha p)P^{32}$ and $Na^{23}(N^{14},\alpha 2p)Si^{31}$. The total cross section at 26 Mev for the first reaction is 91 ± 18 millibarns and for the second reaction 4.1 ± 0.8 millibarns. A calculation based on the statistical model of the nucleus gives a value of about 50 for the ratio of $\sigma_{P32}/\sigma_{Si31}$, which may be compared with the experimental ratio of 22 ± 5.

INTRODUCTION

MEASUREMENTS of total cross sections for nuclear reactions produced by nitrogen ions on various target elements have been reported previously.[1] This paper describes the measurement of the cross sections for two reactions produced by nitrogen on sodium. The experiments constitute part of a systematic survey of nuclear reactions which lead to the formation of radioactive residual nuclides from the nitrogen bombardment of light elements. The Coulomb barrier limits the use of 26-Mev nitrogen ions available at this laboratory to the study of reactions in elements lighter than calcium.

The two reactions studied in sodium are $Na^{23}(N^{14},\alpha p)P^{32}$ and $Na^{23}(N^{14},\alpha 2p)Si^{31}$. These reactions were chosen among the many possible ones because of the convenient half-lives of the residual nuclei, and because the similarity of the evaporated particles from the two reactions makes comparison with the predictions of the statistical theory of nuclear reactions relatively easy.

With nitrogen-induced reactions, highly excited compound nuclei may be formed with little likelihood of competition from a direct interaction mechanism. The average energy per nucleon in the incident nitrogen nucleus is less than 1.86 Mev while the Q for the formation of the compound nucleus, A^{37}, is +24.36 Mev. It is therefore likely that $(N^{14},\alpha p)$ or $(N^{14},\alpha 2p)$ reactions such as the ones reported here proceed through a compound nucleus process during which the nitrogen and sodium nuclei fuse and α particles and protons are emitted subsequently. There is, of course, always the possibility that surface reactions are of importance here, and that one has to deal with highly excited portions of nuclear matter rather than with uniformly excited compound nuclei. This experiment does not distinguish between these two mechanisms.

EXPERIMENTAL METHOD

The excitation functions were measured in a manner reported previously.[1] Sodium bromide was chosen for the targets because it is a stable sodium compound unlikely to dissociate at bombardment temperatures. No nuclear reactions are possible with bromine because of its high Coulomb barrier. Sodium bromide crystals were pressed into $\frac{3}{4}$-inch diameter brass molds under a pressure of 40 tons/inch^2. The resulting targets were about $\frac{1}{10}$ inch thick, had a smooth hard surface, and could be stored indefinitely in a desiccator. The targets were bombarded in the external beam of the ORNL 63-inch cyclotron. Thin nickel foils varying in thickness from 0.5 mg/cm^2 to 3.3 mg/cm^2 were placed in front of the targets to degrade the beam energy, so that thick target yields could be measured from 14-Mev to 26-Mev laboratory energy. Bombardments lasted from half an hour to over four hours, depending on the nuclide which was to be counted and on the incident energy. The current to the target was measured and integrated with a vibrating reed electrometer, and simultaneously plotted on a recording microammeter to determine how much the time variations of beam intensity would affect the yields.

Phosphorus-32.—The yields of P^{32} were determined by letting the shorter activities in the target decay for several days and then counting the target under a shielded end-window Geiger counter for 20 to 40 days. The P^{32} was identified from its characteristic 14.3-day half-life, and no chemical separations were necessary.

Silicon-31.—The 2.6-hour half-life of Si^{31} made chemical separation necessary, lest the Si^{31} yields be incorrectly determined in a background of radiation from other nuclides with half-lives of the same order. The sodium bromide target was dissolved in dilute hydrochloric acid and about 10 mg of silicon as $(NH_4)_2SiF_6$ was added. Boric acid was added to complex any possible fluorine activity, giving added assurance that the precipitate of SiO_2 would not be contaminated with this activity. Five milliliters of concentrated HCl was added and SiO_2 precipitated by digestion. The precipitate was carefully washed with warm dilute hydrochloric acid. The SiO_2 was dissolved in a minimum of KOH and the solution made strongly acid with HCl; SiO_2 was again precipitated by digestion. Dissolution and precipitation were repeated twice more. The SiO_2 was then filtered, ignited, and weighed to determine chemical yields. After the chemical separation SiO_2 was counted in a shielded calibrated Geiger counter.

[1] H. L. Reynolds and A. Zucker, Phys. Rev. **96**, 1615 (1954); Reynolds, Scott, and Zucker, Phys. Rev. **102**, 237 (1956); Webb, Reynolds, and Zucker, Phys. Rev. **102**, 749 (1956).

RESULTS

The thick-target yields for the two reactions in sodium are shown in Fig. 1. The observed counting rates were corrected for electron back-scattering by using the measurements of Zumwalt,[2] and for counter efficiency by comparison with a RaE standard obtained from the National Bureau of Standards. Each corrected counting rate was converted to a thick-target yield by taking into account the chemical yield, beam current, and bombardment time. The standard error in the absolute value of the yields is about 15%, mostly due to inaccuracies in Geiger counter calibrations. The relative errors in the yields are somewhat smaller, as may be seen from the inspection of the yield curves.

By differentiating the smooth curves drawn to fit the experimental yield points, one obtains the cross section as a function of energy, shown in Fig. 2. The stopping power of NaBr for nitrogen ions was calculated from the known stopping power of nickel for nitrogen and the relative stopping power for nickel and NaBr for protons of the same velocity as the nitrogen ions. The proton stopping powers were taken from Allison and Warshaw.[3] This method of calculating the range of nitrogen ions in various materials has been checked experimentally before for silver and aluminum.[1] The errors in the absolute values of the cross sections are about 20%.

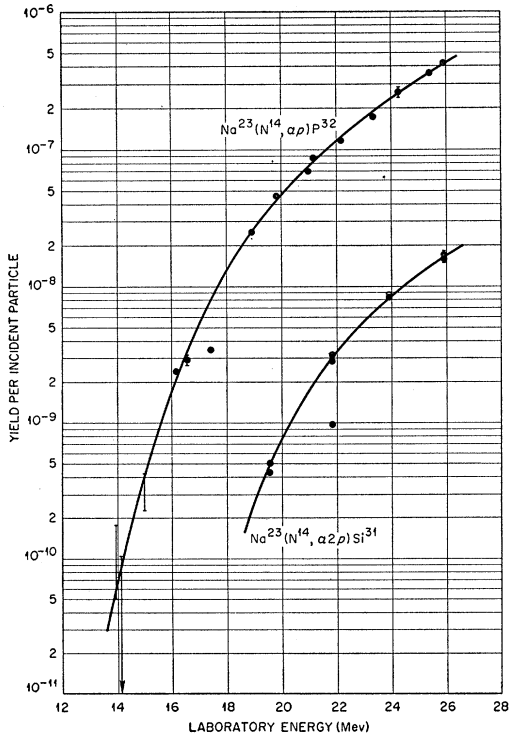

FIG. 1. Thick-target yields for the two reactions $Na^{23}(N^{14},\alpha p)P^{32}$ and $Na^{23}(N^{14},\alpha 2p)Si^{31}$ as a function of incident nitrogen energy.

[2] L. R. Zumwalt, U. S. Atomic Energy Commission Report MDDC-1346, 1947 (unpublished).

[3] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. **25**, 779 (1953).

DISCUSSION

It is assumed that the two reactions investigated are examples of evaporation of nuclear particles from highly excited nuclei. At 26 Mev laboratory energy, the compound nucleus A^{37} is formed with an excitation energy of 40.5 Mev. It can decay to P^{32} by (αp) or $(p\alpha)$ emission and to Si^{31} by (αpp), $(p\alpha p)$, or $(pp\alpha)$ emission. Calculations described below show that the $(pp\alpha)$ process accounts for less than 10% of the Si^{31} formed since it is improbable that enough energy will remain in the nucleus, after the evaporation of two protons, for an α particle to be emitted with sufficient energy to penetrate the exit Coulomb barrier. Therefore, it can be seen that Si^{31} is, so to speak, a daughter of P^{32}, and that the amount of Si^{31} will depend on the energy level in which P^{32} is left after an α particle and a proton have been emitted from the compound nucleus. There are, to be sure, other routes involving deuterons, tritons, or He^3 by which the compound nucleus can decay to P^{32} or Si^{31}. These are, however, energetically unfavored and have been neglected.

TABLE I. Comparison of calculated values and experimental results. Only one of the absolute cross sections σ_{P32} and σ_{Si31} is an independent quantity, but both are listed for comparison with experimental results. The calculations listed are for two values of a, and for $r_0=1.5\times10^{-13}$ cm.

		$\sigma_{P32}/\sigma_{A37}$	$\sigma_{Si31}/\sigma_{A37}$	σ_{P32} millibarns	σ_{Si31} millibarns	$\sigma_{P32}/\sigma_{Si31}$
Calculated values	$a=2.6$	0.1917	6.14×10^{-4}	84.2	0.270	312.2
	$a=14.5$	0.0696	13.0×10^{-4}	30.6	0.571	53.5
Experimental values				91 ± 18	4.1 ± 0.8	22 ± 5

If it is assumed that the P^{32} and Si^{31} are formed by particle evaporation, the results of the experiment may be compared with the predictions of the statistical theory of nuclear reactions. This was done at one incident energy, 26 Mev. The following discussion is based on the theory as given by Blatt and Weisskopf.[4] The compound nucleus A^{37} may decay first by the emission of a proton, neutron, α-particle, deuteron, etc. To determine the probability that the first particle will be a proton, the ratio $F_p/\sum F_b$ (in the notation of Blatt and Weisskopf) was calculated. The energy distribution of the emitted protons was calculated from the relation

$$N(E)dE=\text{const}E\sigma_c(E)w(E_r)dE.$$

Here E is the channel energy, $\sigma_c(E)$ is the cross section for the inverse reaction taken from the tables[4] for $r_0=1.50\times10^{-13}$ cm, and E_r is the excitation energy of

[4] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), pp. 352–374.

the residual nucleus. The level density of the residual nucleus, $w(E_r)$, was calculated from the relation

$$w(E_r)=C\exp[(aE_r)^{\frac{1}{2}}].$$

The choice of the constants is discussed below. From the probability that protons are emitted and from the proton energy distribution, the population density of the various available states in Cl^{36} was obtained. To simplify the calculation, the protons were grouped corresponding to energy level bands 5 Mev wide in the residual nucleus. By proceeding in the same manner for α particles evaporated from Cl^{36}, the population of states in P^{32} (grouped this time into 2-Mev bands) was obtained. Low-lying states of P^{32} decay by γ-ray emission to the ground state while higher states may decay to Si^{31} by proton emission, again with a predictable probability. In a similar way the contributions to the formation of P^{32} and Si^{31} by the other decay routes involving protons and α particles were calculated.

Adding all contributing decay modes gives the number of P^{32} (or Si^{31}) nuclei formed per A^{37} nucleus. This is equal to $\sigma_{P32}/\sigma_{A37}$ (or $\sigma_{Si31}/\sigma_{A37}$) where σ_{A37} is the cross section for formation of the compound nucleus. Table I gives these ratios for two choices of the parameter a. The smaller value, $a=2.6$, was obtained by interpolating from the table given by Blatt and Weisskopf.[4] The larger value, $a=14.5$, is based on the work of Lang and Le Couteur.[5] The magnitude of the parameter C is irrelevant here, but the dependence of the level density on the odd-even character of the nucleus was taken into account by doubling C for odd-odd nuclei and halving it for even-even nuclei, relative to its value for nuclei of odd atomic mass number.

Two independent calculated values, the ratio of the cross sections $\sigma_{P32}/\sigma_{Si31}$, and the magnitude of one of the cross sections, may be compared with experimental results. The latter quantity involves the capture cross section of nitrogen by sodium (σ_{A37}). This is calculable if the penetrabilities are known, but the existing tables do not cover the full range of parameters needed because of the large mass of the nitrogen. The approximate formula,

$$\sigma_c=\pi(R+\lambda\!\!\!^{-})^2\left[1-\frac{R}{(R+\lambda\!\!\!^{-})E/B}\right],$$

gives results in reasonable agreement with the more exact calculation so long as the incident energy (E) is ten or twenty percent above the Coulomb barrier (B). This is unfortunately not the case here, but the results of this calculation are given for σ_{P32} in Table I to show approximately how the choice of a affects the absolute value of the P^{32} cross section. The same has been done for the Si^{31} cross section.

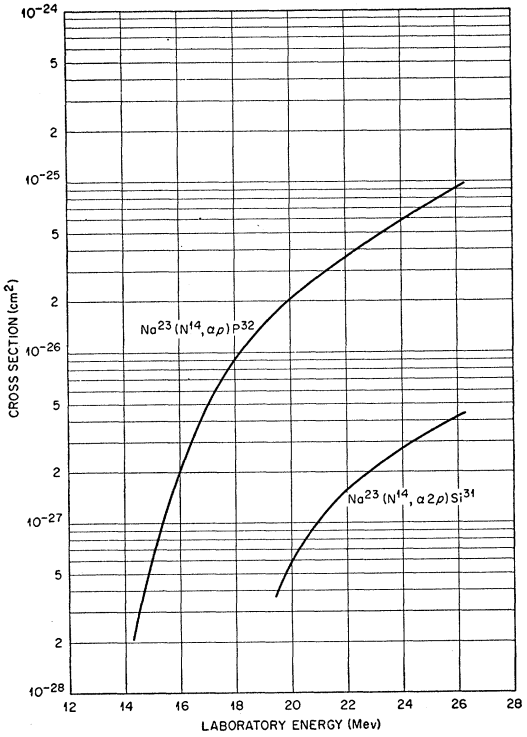

FIG. 2. Cross section as a function of incident nitrogen energy for the two reactions $Na^{23}(N^{14},\alpha p)P^{32}$ and $Na^{23}(N^{14},\alpha 2p)Si^{31}$.

The ratio of σ_{P32} to σ_{Si31}, also given in Table I, is independent of σ_{A37} and probably provides a more meaningful comparison with the experiment. The experimental results at 26 Mev are listed in the last line of Table I. If one compares the experimental ratio with the calculated results, it is clear that the larger a is favored. As pointed out above, a comparison of the magnitudes of σ_{P32} and σ_{Si31} is not very significant. It should be noted, however, that these quantities are not as strongly dependent on a as is the ratio of cross sections, and would not be as sensitive a measure of a even if σ_{A37} were known better. The calculated values of σ_{P32} and σ_{Si31} depend strongly on the nuclear radius used to determine the capture cross section, σ_c. Recent results obtained from nitrogen-nitrogen elastic scattering[6] indicate that $r_0=1.66\times10^{-13}$ cm should be used to calculate σ_c. The larger value of the nuclear radius serves to increase the calculated σ_{P32} and σ_{Si31} by a factor of 1.85, for both values of a.

The authors wish to thank Miss Shirley Hale for assistance in processing the data.

[5] J. M. B. Lang and K. J. Le Couteur, Proc. Phys. Soc. (London) **A67**, 586 (1954).

[6] H. L. Reynolds and A. Zucker, Phys. Rev. **102**, 1378 (1956).